WBS 6.6: Muons Technical Overview

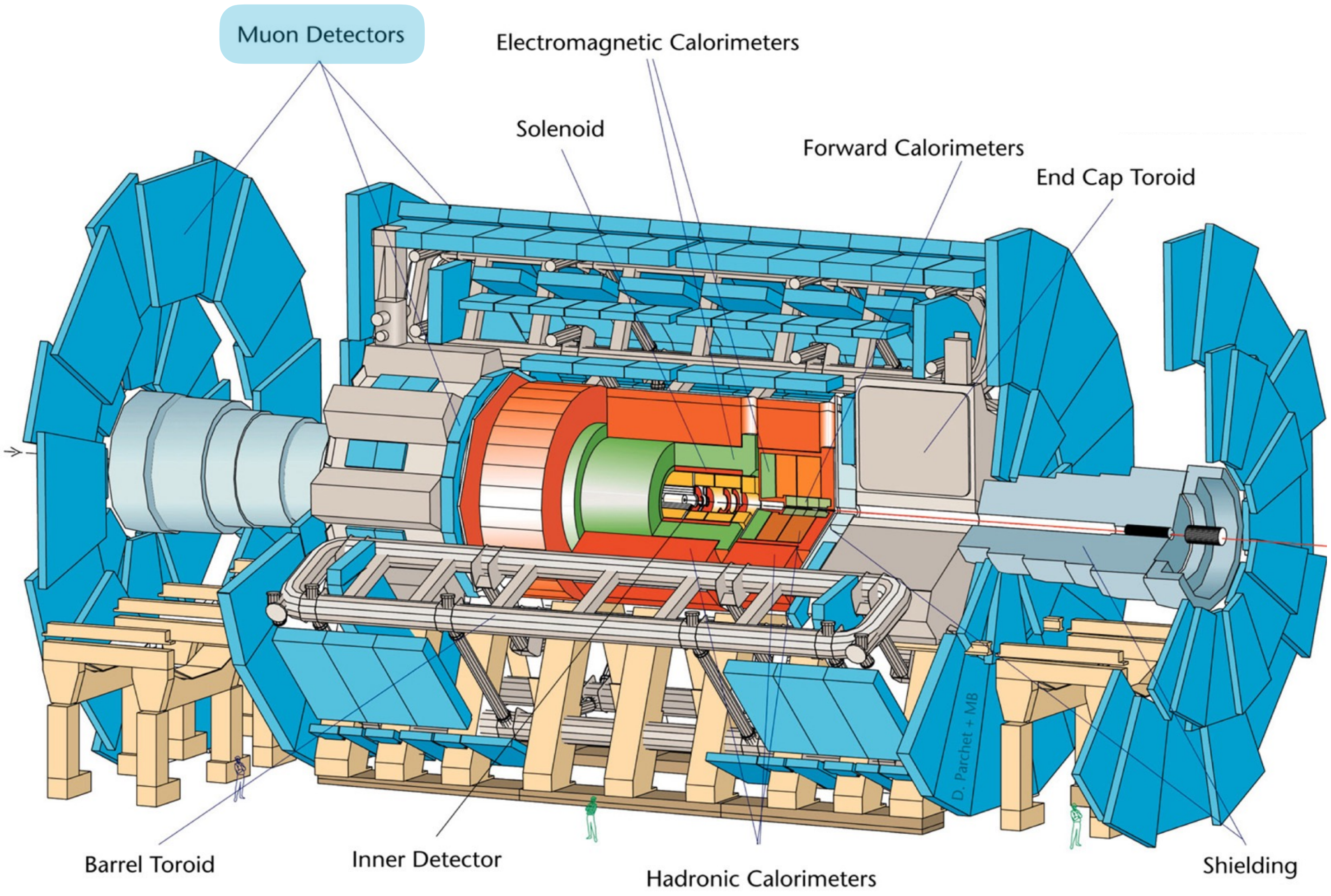
Tom Schwarz
Level-2 Manager
University of Michigan

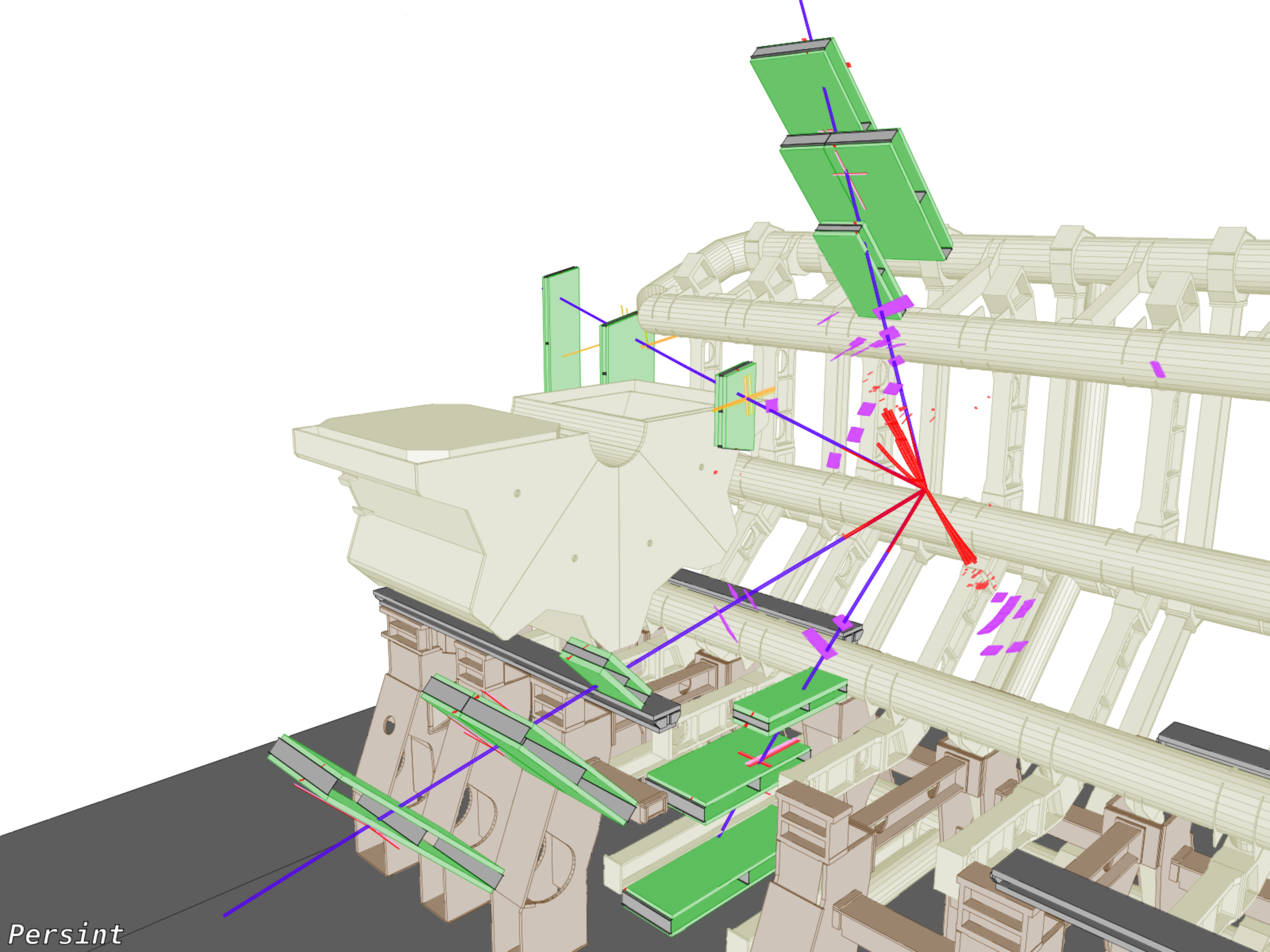
Conceptual Design Review for the High Luminosity LHC Detector Upgrade
National Science Foundation
Arlington, Virginia
March 8-10, 2016

Outline

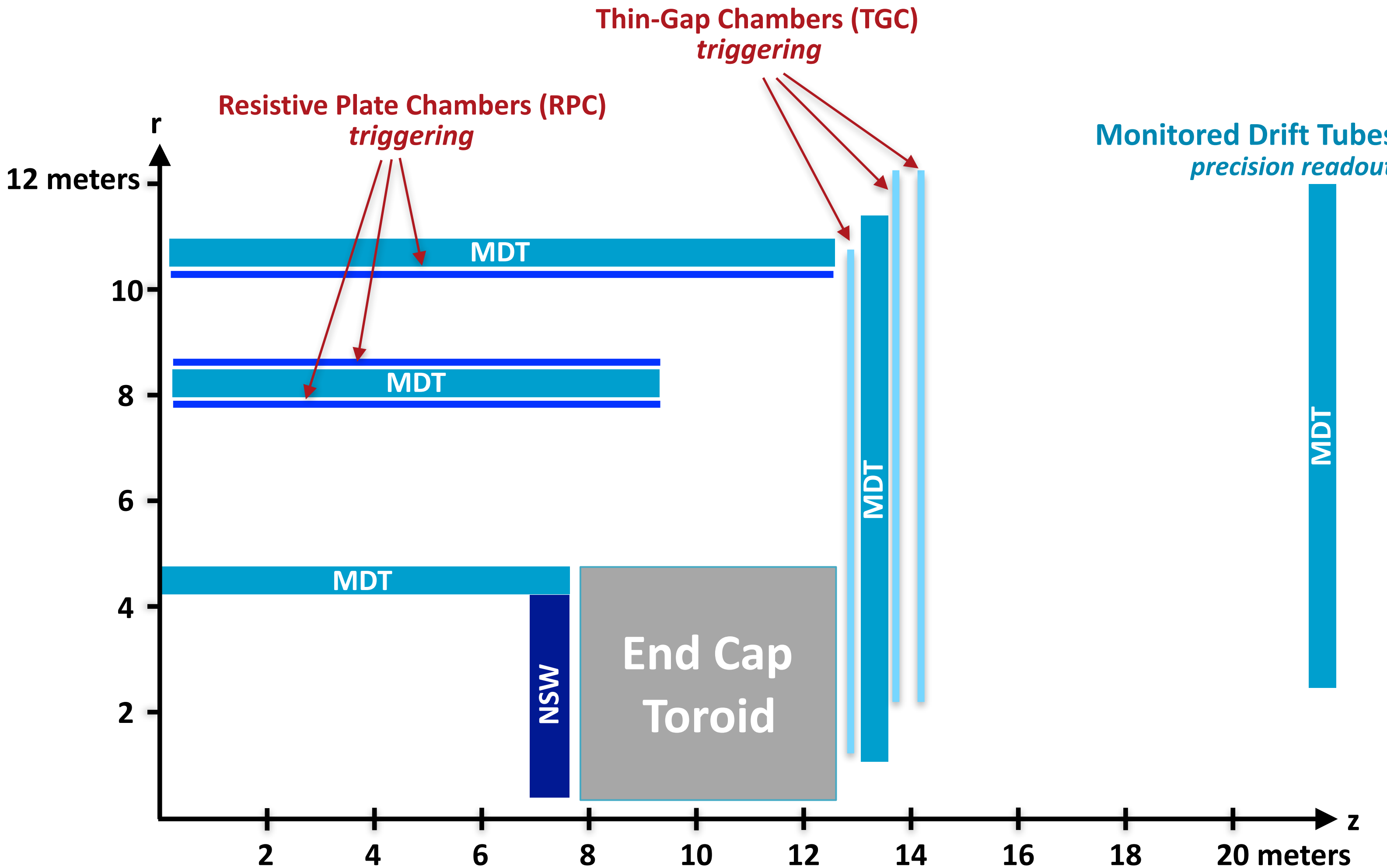
- Muon Spectrometer Overview
- Physics and Technical Requirements
- Proposed US HL-LHC Upgrade Scope
- NSF Deliverables
- Ongoing R&D
- System Management and Integration
- Schedule and Risks

ATLAS Muon Spectrometer




Persint

Muon Spectrometer (r-z view)



ATLAS Muon Upgrade Scope

Upgrades to the muon spectrometer (readout electronics and chambers) are required to handle increased rates and fakes associated with HL-LHC luminosities

To cope with high rates,

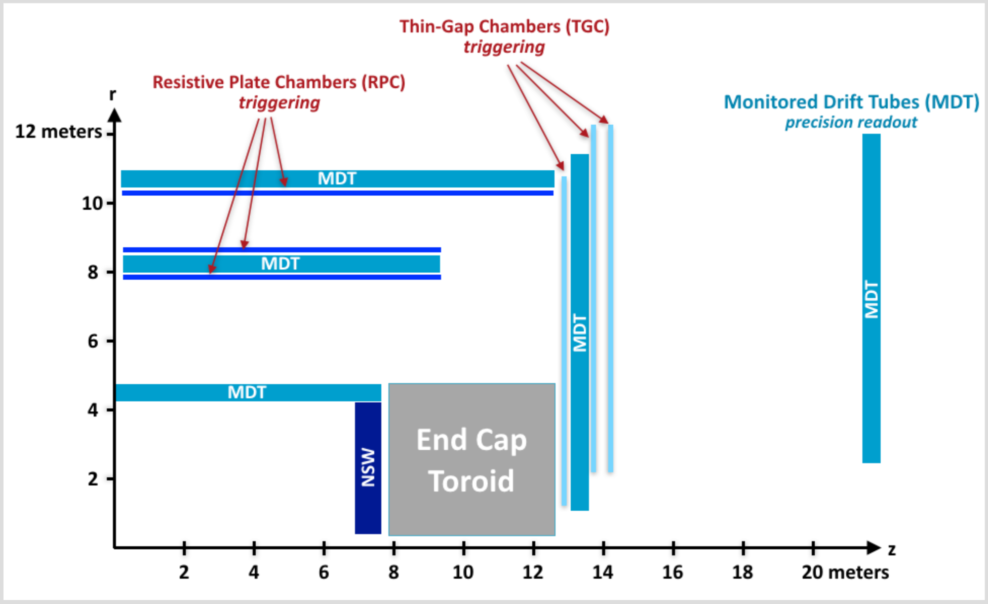
➡ **The readout electronics of the MDT system must be replaced, as well as the barrel (RPC) and end-cap (TGC) triggering system.**

To reduce fakes & improve trigger efficiency

➡ **p_T selectivity of tracks for the trigger will be improved by integrating MDT information into triggering (Level-0).**

➡ **To reduce fakes at high η (2 < |η| < 2.4), new sTGC's will be installed in the inner ring of the big wheel.**

➡ **RPC and sMDT chambers will replace current MDT chambers in the inner barrel to allow for a 3-station MDT trigger**



NSF Scope

Upgrades to the muon spectrometer (readout electronics and chambers) are required to handle increased rates and fakes associated with HL-LHC luminosities

To cope with high rates,

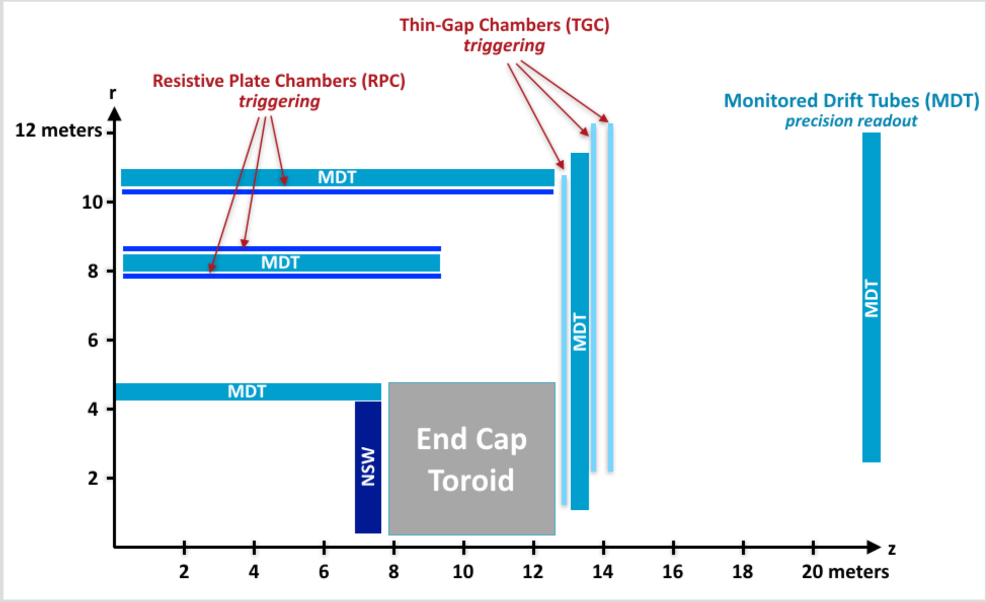
➡ The readout electronics of the MDT system must be replaced, as well as the barrel (RPC) and end-cap (TGC) triggering system.

To reduce fakes & improve trigger efficiency

➡ p_T selectivity of tracks for the trigger will be improved by integrating MDT information into triggering (Level-0).

➡ To reduce fakes at high η (2 < |η| < 2.4), new sTGC's will be installed in the inner ring of the big wheel.

➡ RPC and sMDT chambers will replace current MDT chambers in the inner barrel to allow for a 3-station MDT trigger



NSF Scope

Upgrades to the muon spectrometer (readout electronics and chambers) are required to handle increased rates and fakes associated with HL-LHC luminosities

To cope with high rates,

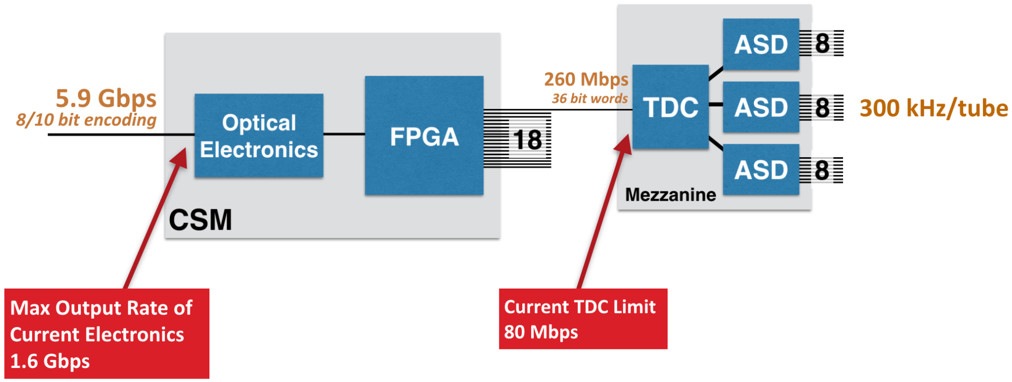
➡ The readout electronics of the MDT system must be replaced, as well as the barrel (RPC) and end-cap (TGC) triggering system.

To reduce fakes & improve trigger efficiency

➡ p_T selectivity of tracks for the trigger will be improved by integrating MDT information into triggering (Level-0).

➡ To reduce fakes at high η ($2 < |\eta| < 2.4$), new sTGC's will be installed in the inner ring of the big wheel.

➡ RPC and sMDT chambers will replace current MDT chambers in the inner barrel to allow for a 3-station MDT trigger



Readout electronics must be able to handle 300 kHz/tube hit rate and a 1 MHz trigger, which is <u>not possible in the current system.</u>

NSF Scope

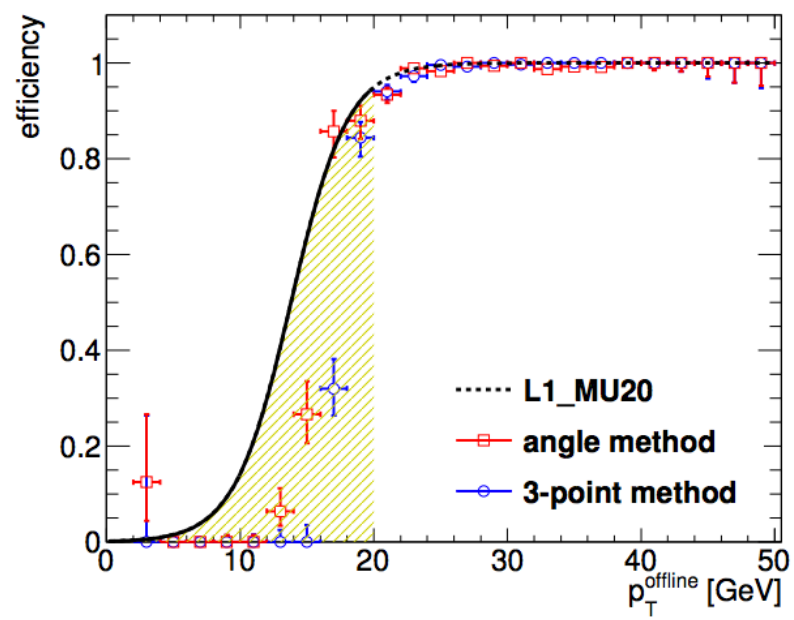
Upgrades to the muon spectrometer (readout electronics and chambers) are required to handle increased rates and fakes associated with HL-LHC luminosities

To cope with high rates,

- The readout electronics of the MDT system must be replaced, as well as the barrel (RPC) and end-cap (TGC) triggering system.

To reduce fakes & improve trigger efficiency

- p_T selectivity of tracks for the trigger will be improved by integrating MDT information into triggering (Level-0).
- To reduce fakes at high η (2 < |η| < 2.4), new sTGC's will be installed in the inner ring of the big wheel.
- RPC and sMDT chambers will replace current MDT chambers in the inner barrel to allow for a 3-station MDT trigger



MDT muon trigger turn-on curves for a two-station (red) and three station (blue) trigger compared with the RPC L0 muon turn-on curve (black) in simulated data. Sharpening the turn-on curve will reduce the muon fake rate by 4x.

NSF Scope

Upgrades to the muon spectrometer (readout electronics and chambers) are required to handle increased rates and fakes associated with HL-LHC luminosities

To cope with high rates,

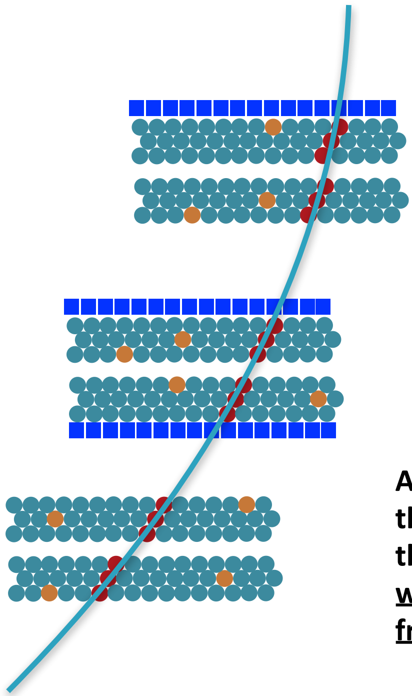
➡ The readout electronics of the MDT system must be replaced, as well as the barrel (RPC) and end-cap (TGC) triggering system.

To reduce fakes & improve trigger efficiency

➡ p_T selectivity of tracks for the trigger will be improved by integrating MDT information into triggering (Level-0).

➡ To reduce fakes at high η (2 < |η| < 2.4), new sTGC's will be installed in the inner ring of the big wheel.

➡ RPC and sMDT chambers will replace current MDT chambers in the inner barrel to allow for a 3-station MDT trigger



Adding RPC/MDT detectors to the inner barrel will allow for three-station triggering. This will improve trigger efficiency from 65 to 95% at the HL-LHC.

HL-LHC Science Goals

SCIENCE GOALS	SCIENCE REQUIREMENTS	NSF SCOPE
$H \rightarrow 4\mu$ (2.2%) VBF $H \rightarrow ZZ^*, WW^*$ (17%,14%) VBS ssWW (5.9%) SUSY $\chi_1^\pm \chi_2^0 \rightarrow \ell bb+X$ (850 GeV)	Muon Trigger • single μ p_T threshold ~ 20 GeV • geometric accept: 95% (barrel)	• Muon Electronics • Tile Electronics • sMDT • L0Muon
VBF $H \rightarrow ZZ^*, WW^*$ (17%,14%) VBS ssWW (5.9%) SUSY $\chi_1^\pm \chi_2^0 \rightarrow \ell bb+X$ (850 GeV)	Electron Trigger • single e p_T threshold ~ 22 GeV	• LAr+Tile Electronics • L1Global • L1Track/FTK++
$HH \rightarrow 4b$ (4.4σ KK Graviton)	Jet Triggers • 4-jet E_T threshold ~ 75 GeV • "fat" jet threshold ~ 375 GeV • jet-vertex confirmation at L1	• Lar+Tile Electronics • L1Global • L1Track/FTK++
Compressed SUSY ($\chi_1^\pm \chi_2^0$)	Missing E_T Trigger • ME_T threshold ~ 200 GeV • track-based ME_T correction	• Lar+Tile Electronics • L1Global • L1Track/FTK++

Cost-Effective Trigger System that meets Science Requirements:
- <L0 accept>=1 MHz (6/10μs); <L1 accept>=400 kHz (30/60μs); <to storage>=10 kHz

HL-LHC Science Goals

SCIENCE GOALS		SCIENCE REQUIREMENTS		NSF SCOPE
$H \rightarrow 4\mu$ (2.2%) VBF $H \rightarrow ZZ^*$, WW^* (17%,14%) VBS ssWW (5.9%) SUSY $\chi_1^{\pm}\,\chi_2^{0} \rightarrow \ell bb+X$ (850 GeV)	→	Muon Trigger • single μ p_T threshold ~ 20 GeV • geometric accept: 95% (barrel)	→	• Muon Electronics • Tile Electronics • sMDT • L0Muon

Triggering and recording High-p_T leptons (muons) are critical to nearly every physics objective of the ATLAS experiment.

Example: Higgs → 4μ

SCIENCE GOALS

$H \rightarrow 4\mu$ (2.2%)
VBF $H \rightarrow ZZ^*, WW^*$ (17%,14%)
VBS ssWW (5.9%)
SUSY $\chi_1^\pm \chi_2^0 \rightarrow \ell bb+X$ (850 GeV)

→

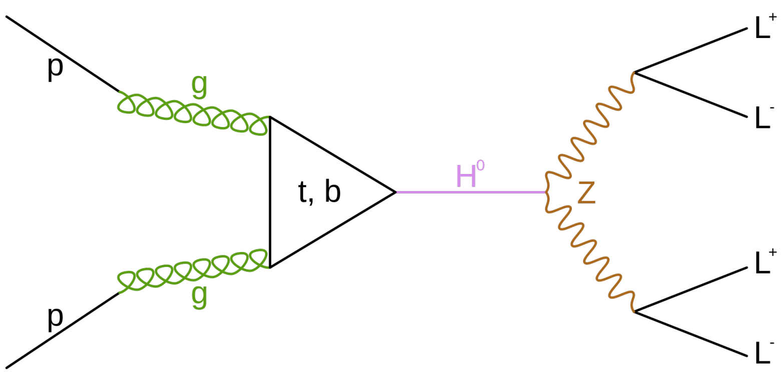
SCIENCE REQUIREMENTS

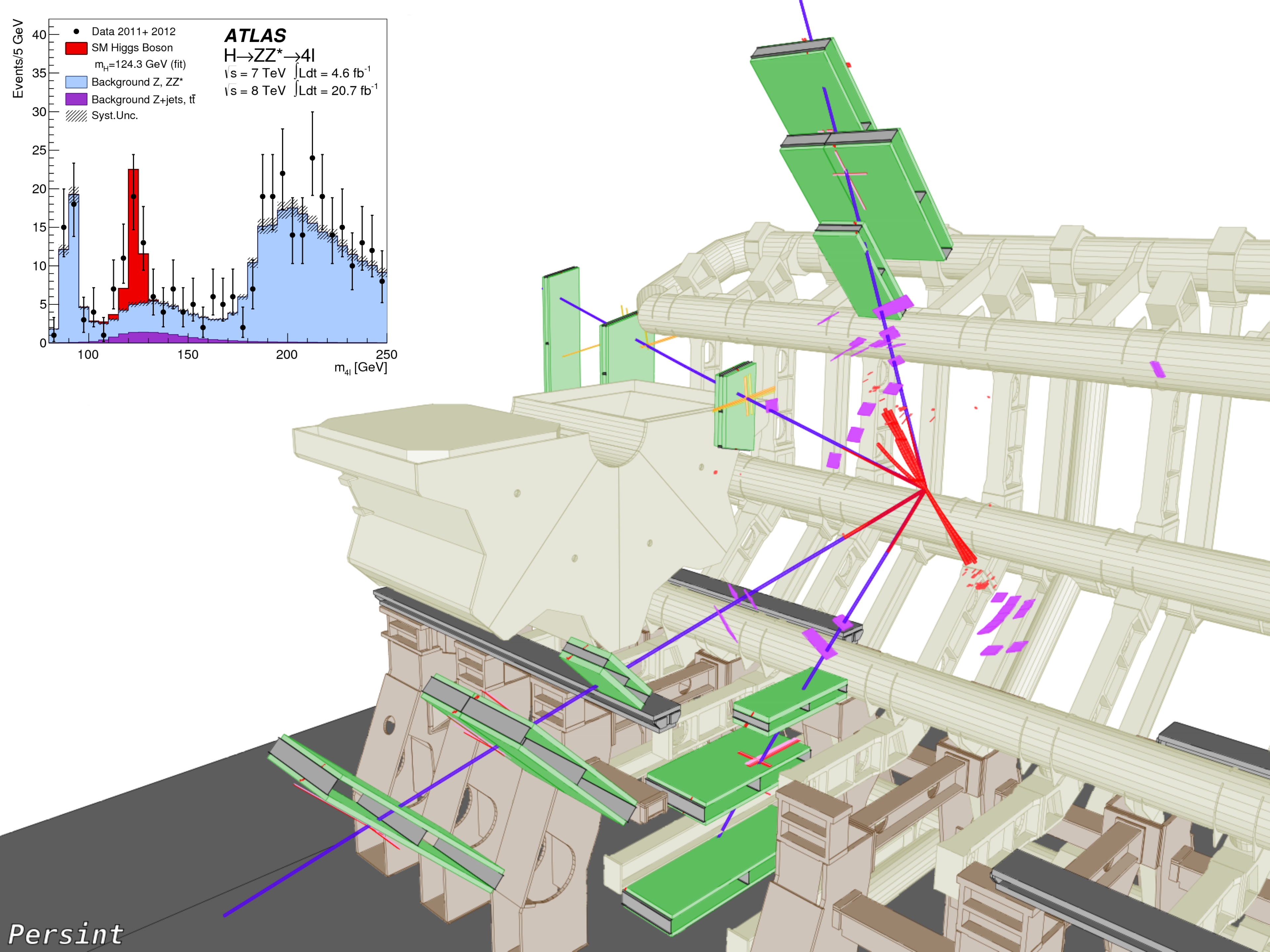
Muon Trigger
- single μ p_T threshold ~ 20 GeV
- geometric accept: 95% (barrel)

→

NSF SCOPE

- Muon Electronics
- Tile Electronics
- sMDT
- L0Muon




Data 2011+ 2012
SM Higgs Boson
m_H=124.3 GeV (fit)
Background Z, ZZ*
Background Z+jets, tt̄
Syst.Unc.
ATLAS
H→ZZ*→4l
√s = 7 TeV ∫Ldt = 4.6 fb⁻¹
√s = 8 TeV ∫Ldt = 20.7 fb⁻¹
Events/5 GeV
m_4l [GeV]
Persint

Example: Higgs → 4μ

SCIENCE GOALS

H → 4μ (2.2%)
VBF H → ZZ*, WW* (17%,14%)
VBS ssWW (5.9%)
SUSY $\chi_1^{\pm}\,\chi_2^{0} \rightarrow \ell bb+X$ (850 GeV)

→

SCIENCE REQUIREMENTS

Muon Trigger
- single μ p_T threshold ~ 20 GeV
- geometric accept: 95% (barrel)

→

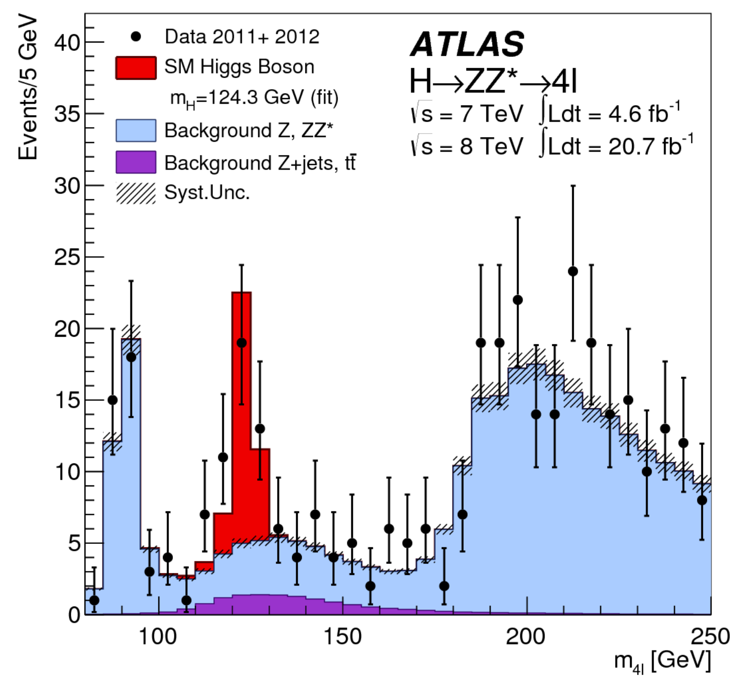
NSF SCOPE

- Muon Electronics
- Tile Electronics
- sMDT
- L0Muon

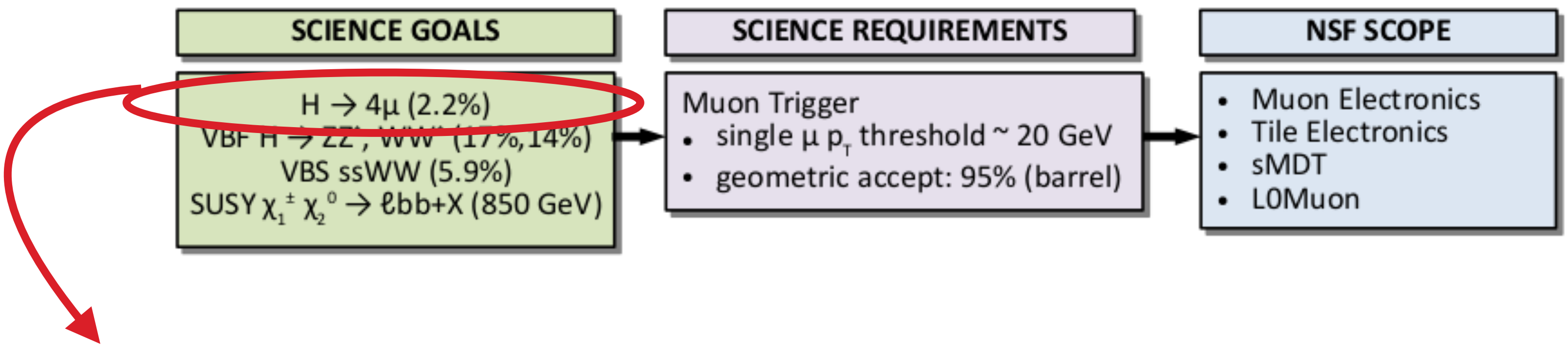
- **Many new physics models result in <u>small</u> differences in the rate of Higgs boson production with respect to the standard model (Higgs Composite Models). This necessitates precision measurements of rates in all channels.**

- **2.2% represents maximizing the potential of the experiment for this measurement (statistical uncertainty = systematic uncertainty)**

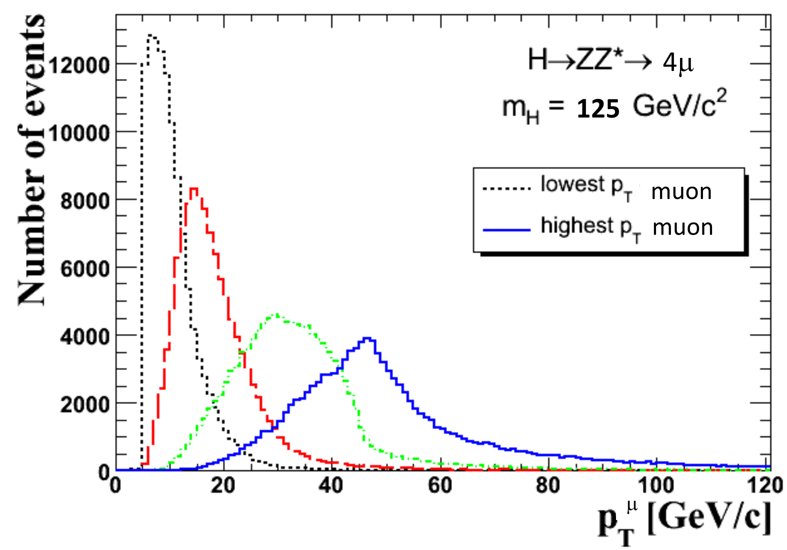
- **The measurement precision of the h➔4μ rate is driven by statistics (event acceptance)**



Example: Higgs → 4μ



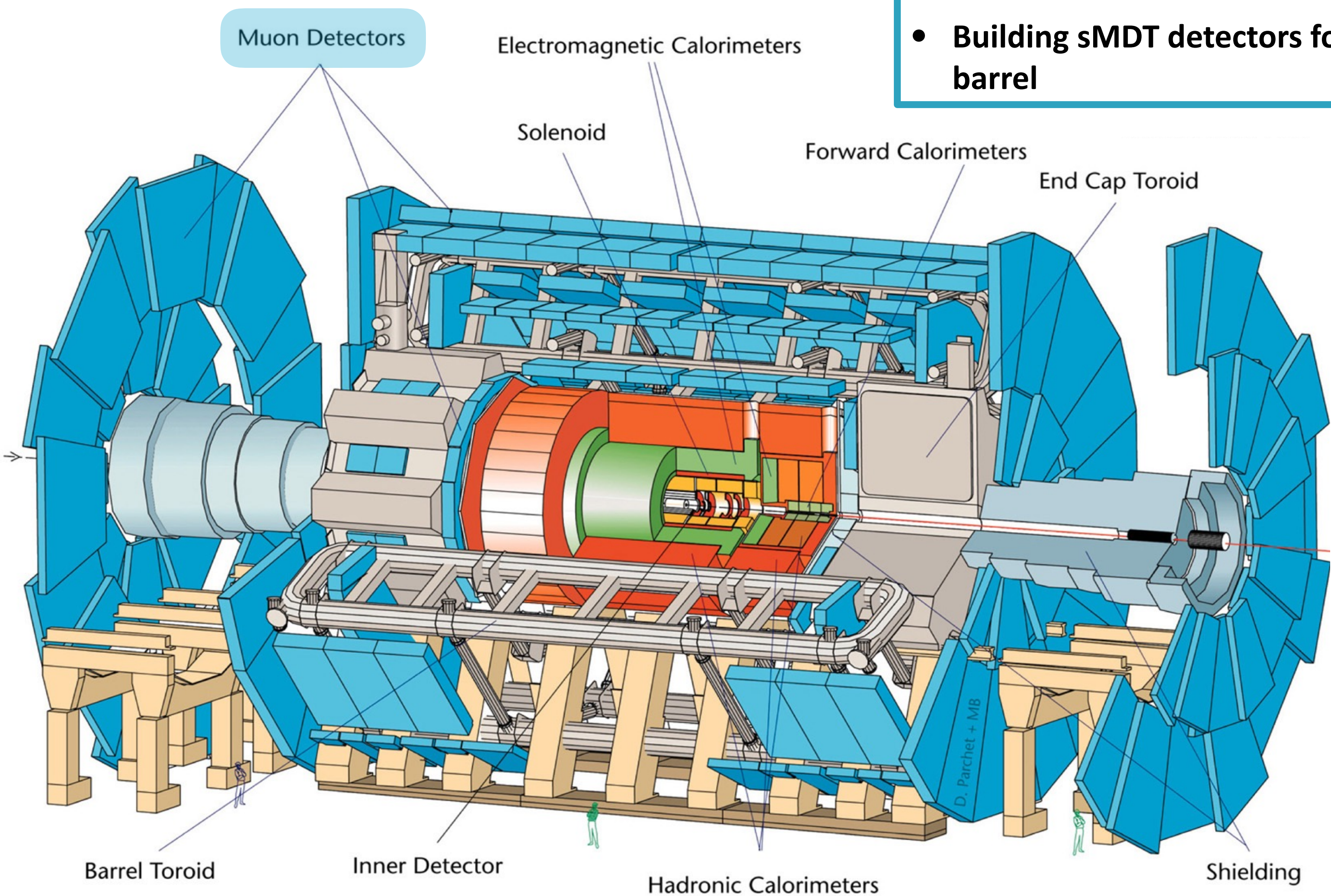
- Without the HL-LHC upgrade, we cannot handle the increased trigger rates, and therefore can't maintain the single muon p_T threshold of 20 GeV
- To handle the increased background rates we could raise the trigger threshold to 40 GeV.
- However, this would decrease the h→4μ acceptance by factor of ~2.
- To reach maximum potential of the experiment, we would then need to run the experiment 2x longer (assuming hardware could withstand this lifetime)



NSF Scope: MDT System

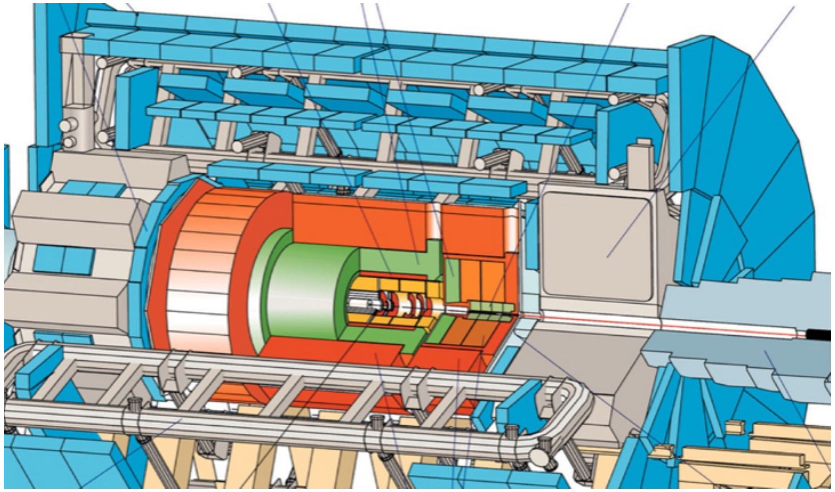
Improving Trigger Efficiency and Precision Tracking

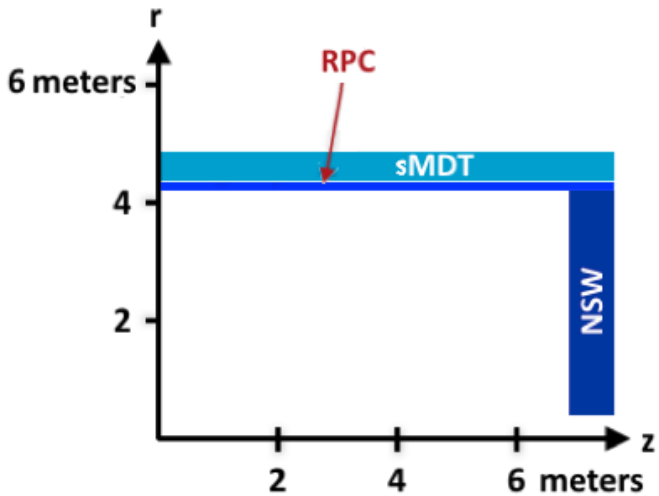
- **Replacing readout electronics for the entire MDT system (blue)**
- **Building sMDT detectors for the inner barrel**



6.6.x.5 sMDT Detectors

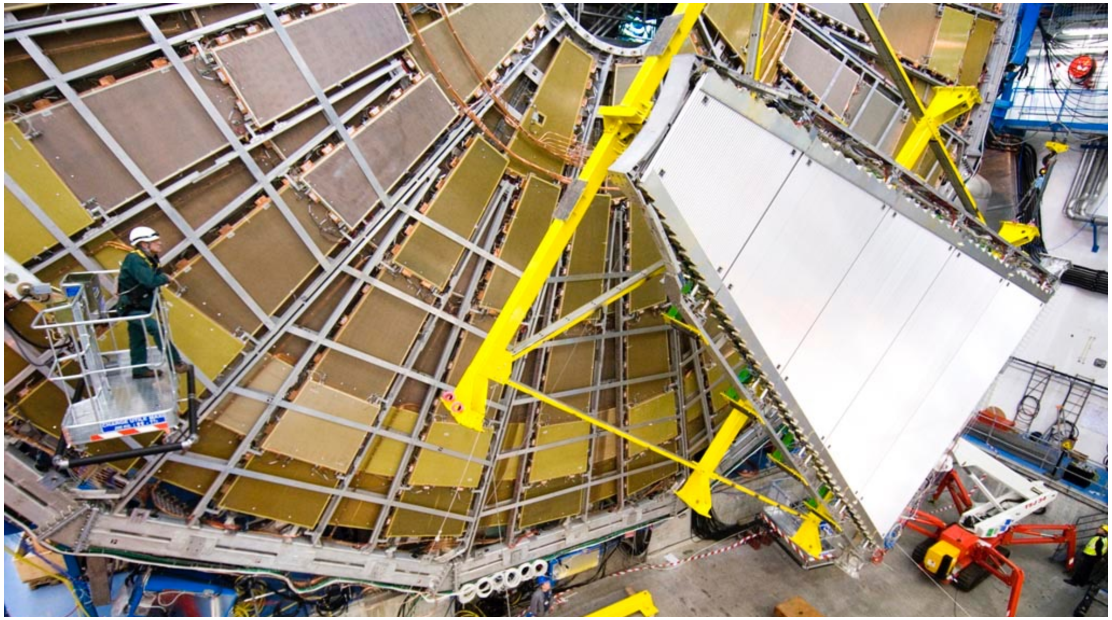
- 48 short monitored drift chambers will be constructed by Michigan State University (tubes, 6.6.5.5) and the University of Michigan (chambers, 6.6.3.5).
- This represents 50% of the total number of chambers that need to be built. The other 50% will be constructed by Protovino (tubes) and the Max Planck Institute (chambers).
- Michigan constructed MDT chambers for the current ATLAS Big Wheel in the End Cap of the Muon Spectrometer. Existing infrastructure is still in place and tooling already is available at MPI. Michigan State University has mechanical experience and a great deal of existing infrastructure.

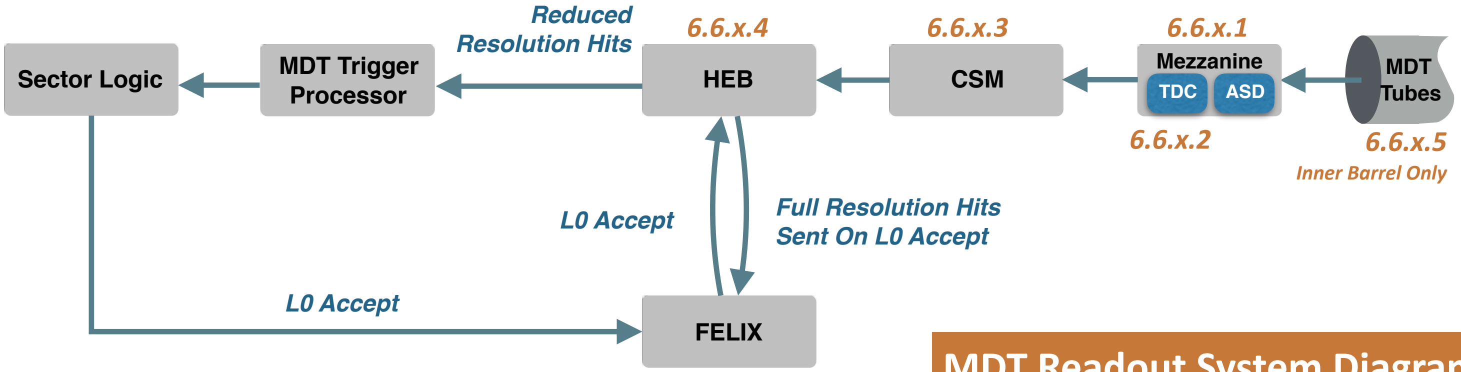




MDT Readout Electronics

Lowering and Installation of the first sector of the MDT Muon Big Wheel on side C of the ATLAS cavern. (TGC wheel in background)

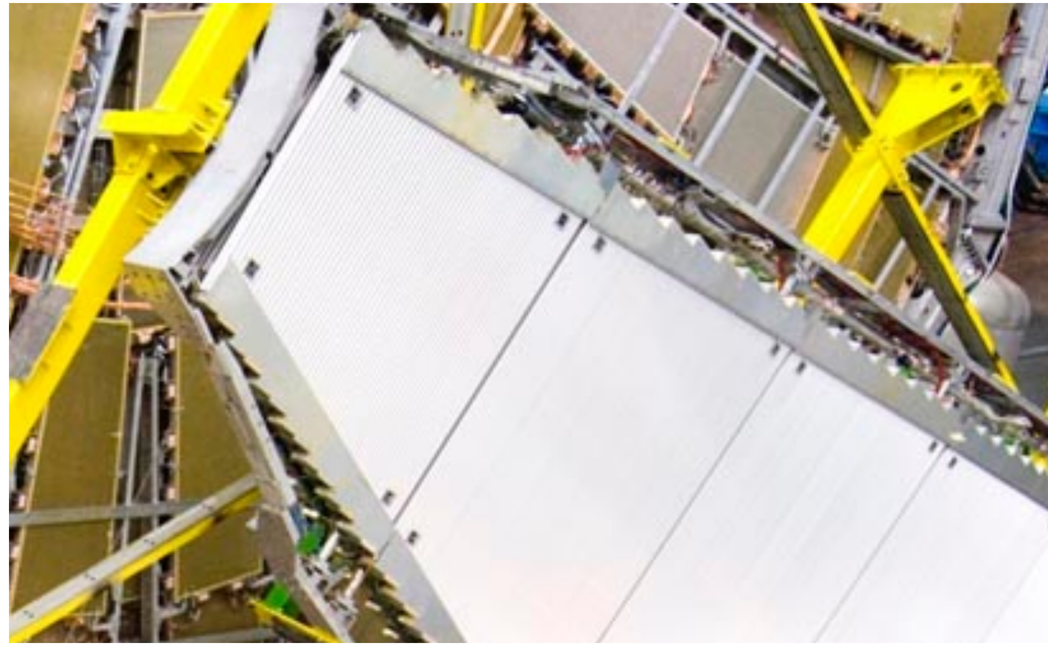


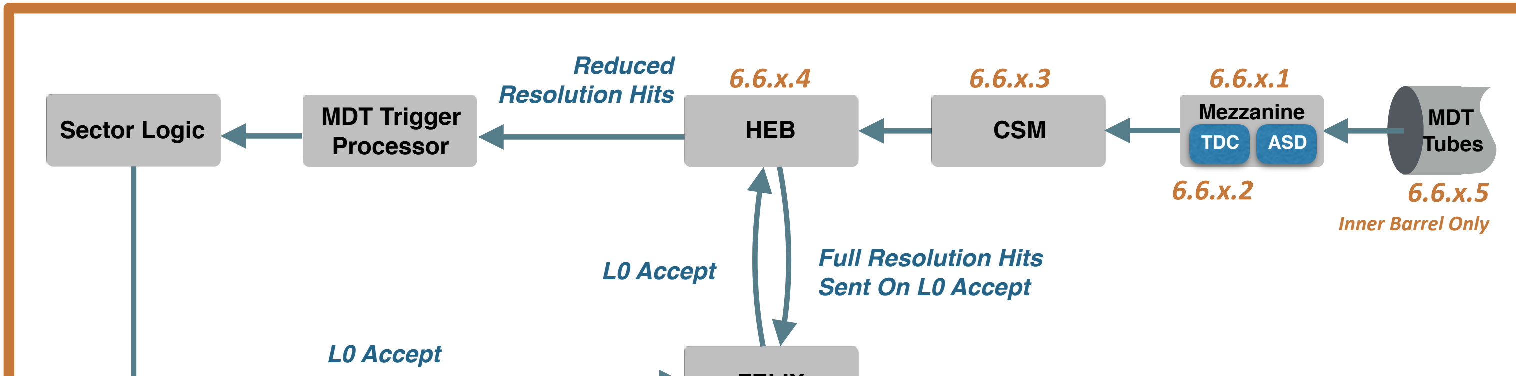


MDT Readout System Diagram

MDT Readout Electronics

Lowering and Installation of the first sector of the MDT Muon Big Wheel on side C of the ATLAS cavern. (TGC wheel in background)

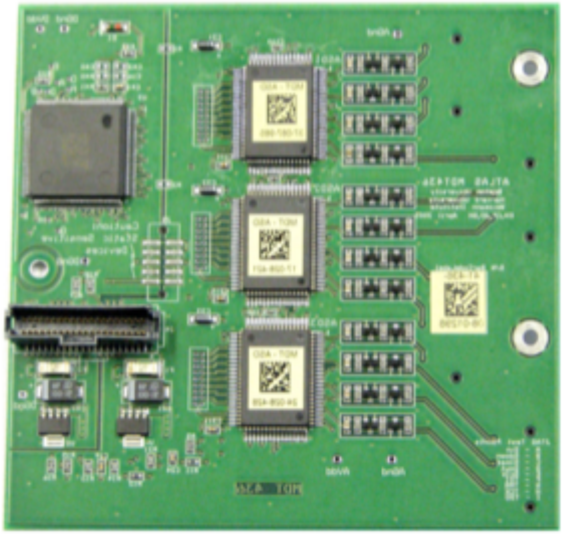


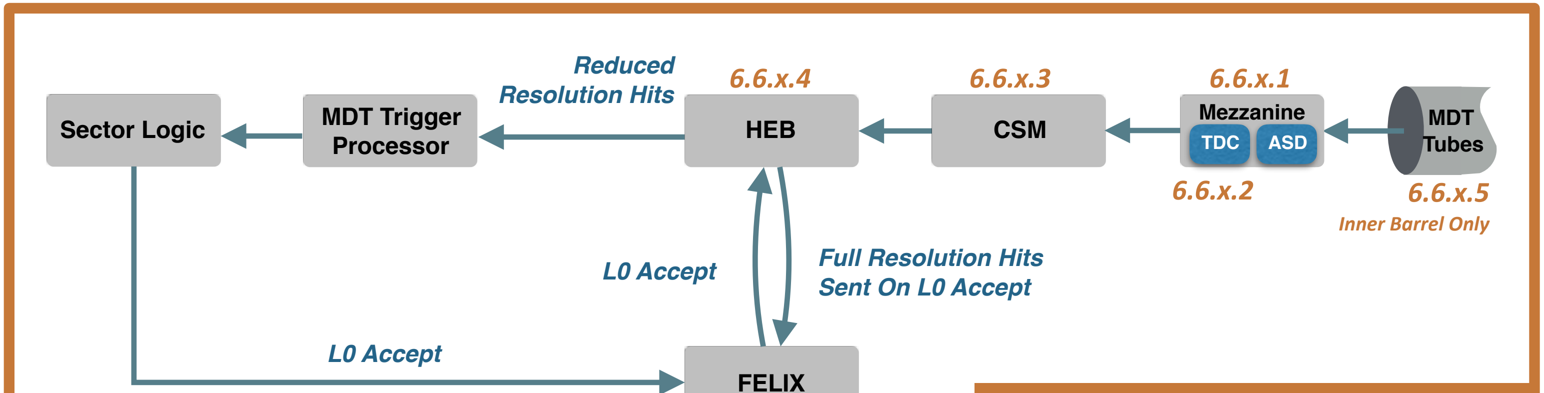


MDT Readout System Diagram

6.6.x.1 Mezzanine Board

- The mezzanine board holds three amplifier shaper discriminator (ASD) chips and one time-to-digital converter (TDC) chip.
- 17,725 mezzanine boards will be constructed by the University of Arizona (6.6.1.1). This represents 100% of the required boards. There is no international competition.
- Arizona developed similar boards used for front-end chips for other ATLAS upgrades (Phase I), which was a far more challenging board.

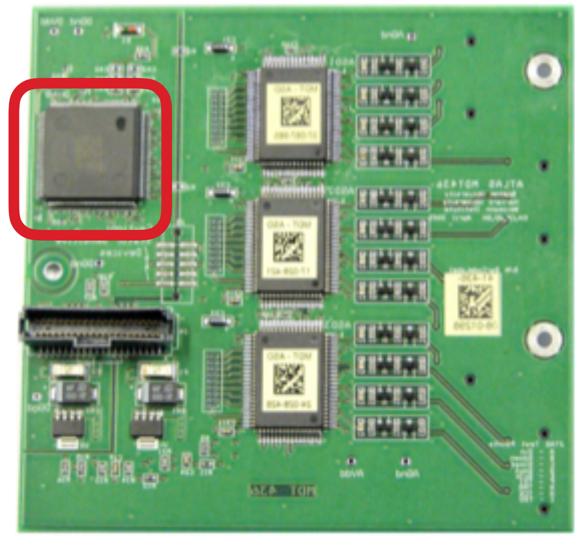


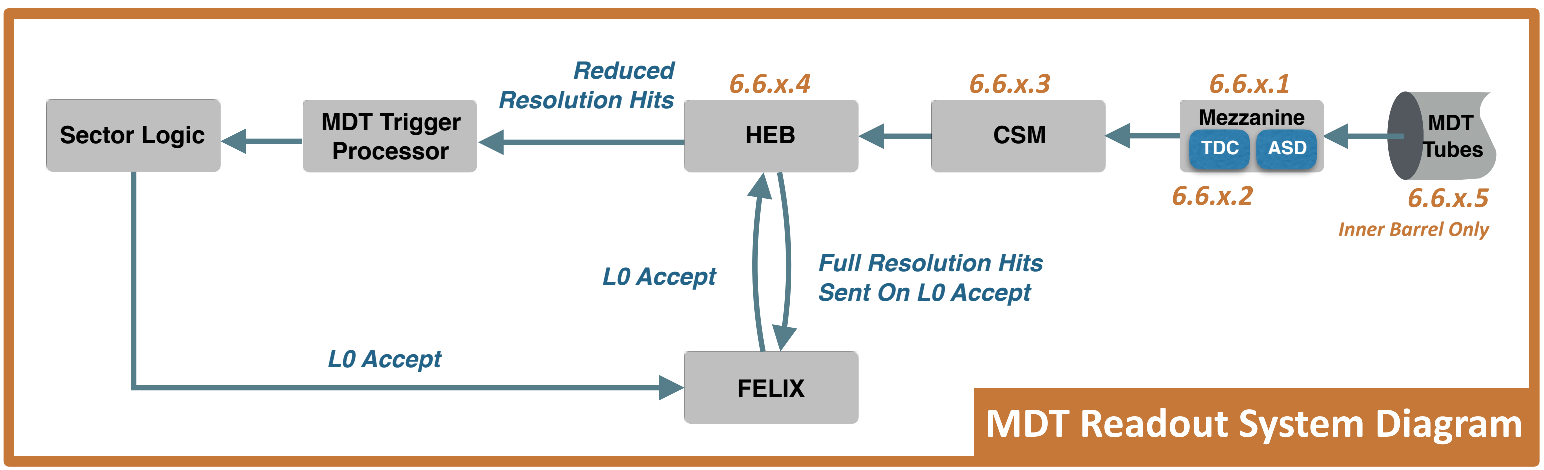


MDT Readout System Diagram

6.6.x.2 TDC

- The TDC produces arrival times of leading and trailing edges of tube signals, as well as an identifier word for the corresponding tube.
- 22,000 time-to-digital converter (TDC) chips will be constructed by the University of Michigan (6.6.3.2). This represents 100% of the required TDC chips.
- Two US designs are being considered (Michigan and BNL). There is international competition from Japan. The down-selection will occur in 2017 (TDR).

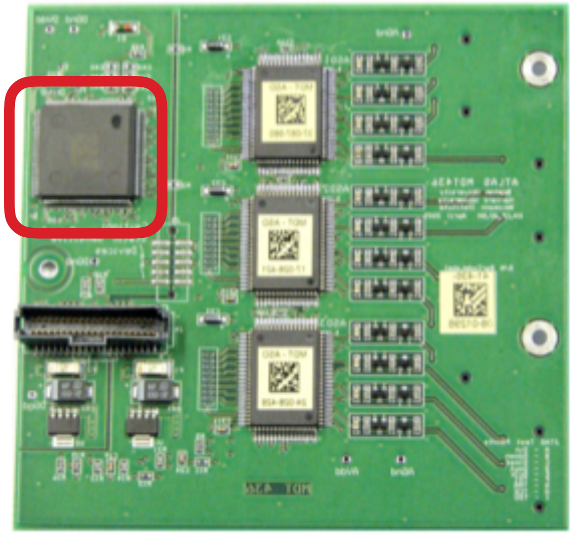


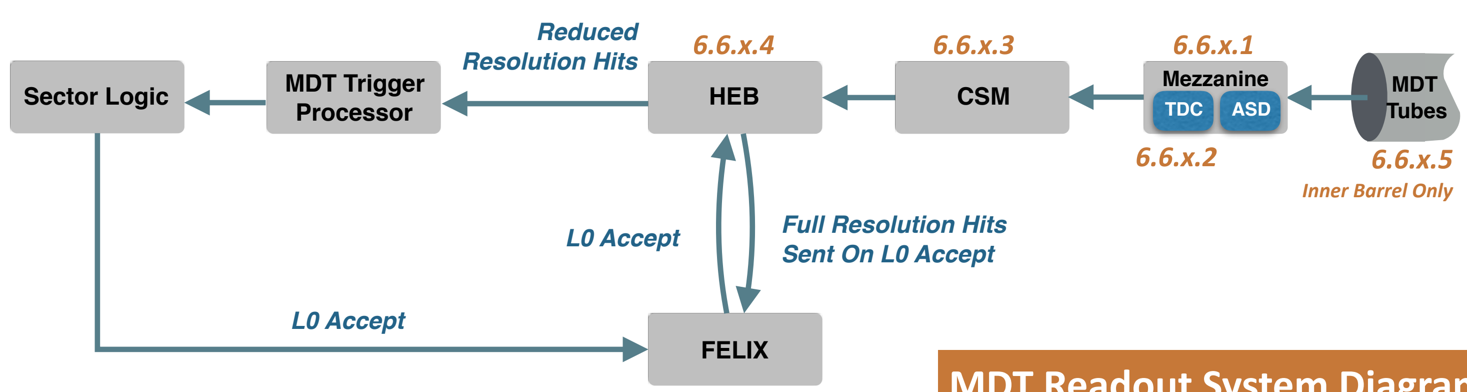


MDT Readout System Diagram

6.6.x.2 TDC

- The University of Michigan developed the trigger data serializer (130 nm IBM ASIC) which is used for detector readout in the Phase I ATLAS upgrade (sTGC detectors in the New Small Wheel).
- The TDC will also be developed in 130 nm IBM.

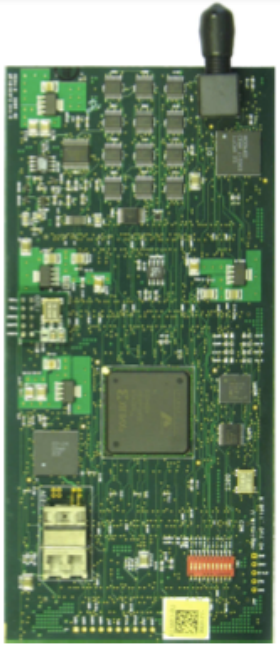


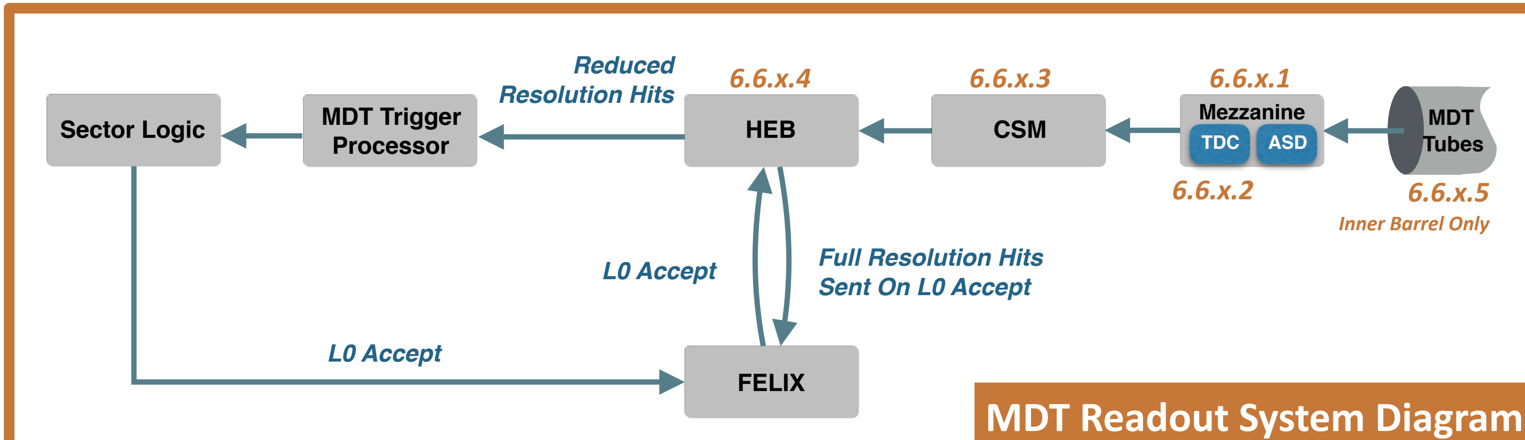


MDT Readout System Diagram

6.6.x.3 CSM

- Up to 18 mezzanine cards, are controlled by a local processor board called the Chamber Service Module (CSM)
- The CSM broadcasts the control signals to the TDCs, and collects data from them
- At the CSM, data are formatted, stored, and sent via optical link to the Hit Extraction Board (HEB).
- 1300 CSM boards will be constructed by the University of Michigan (6.6.3.3). This represents 100% of the required CSM boards for ATLAS. There is no international competition.

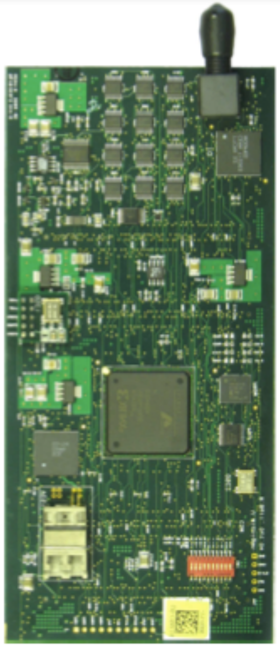


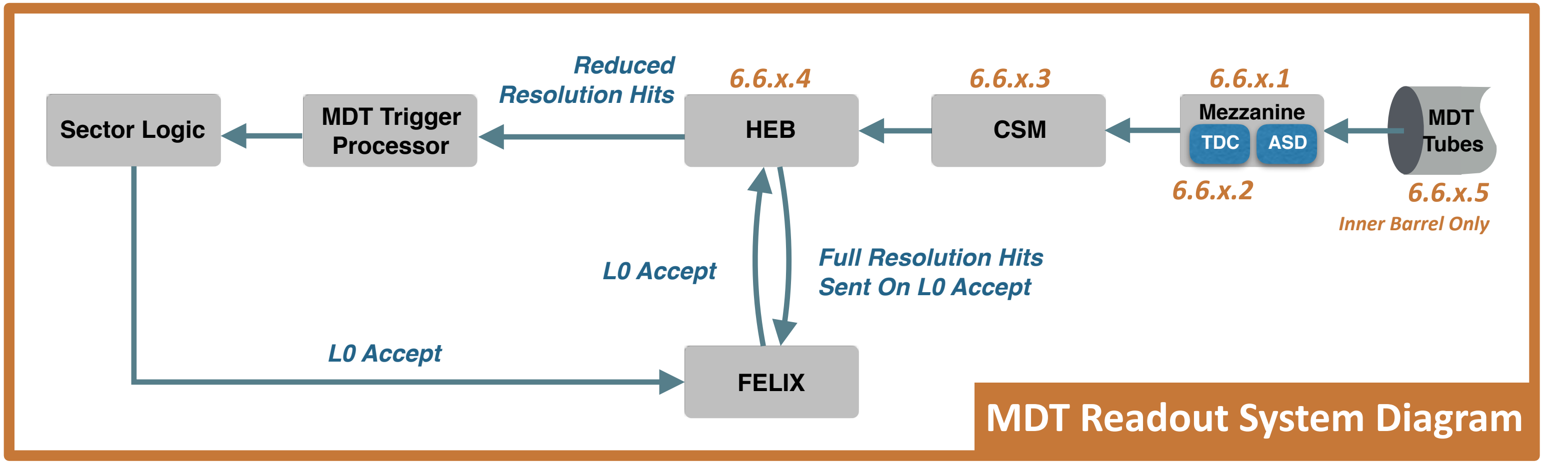


MDT Readout System Diagram

6.6.x.3 CSM

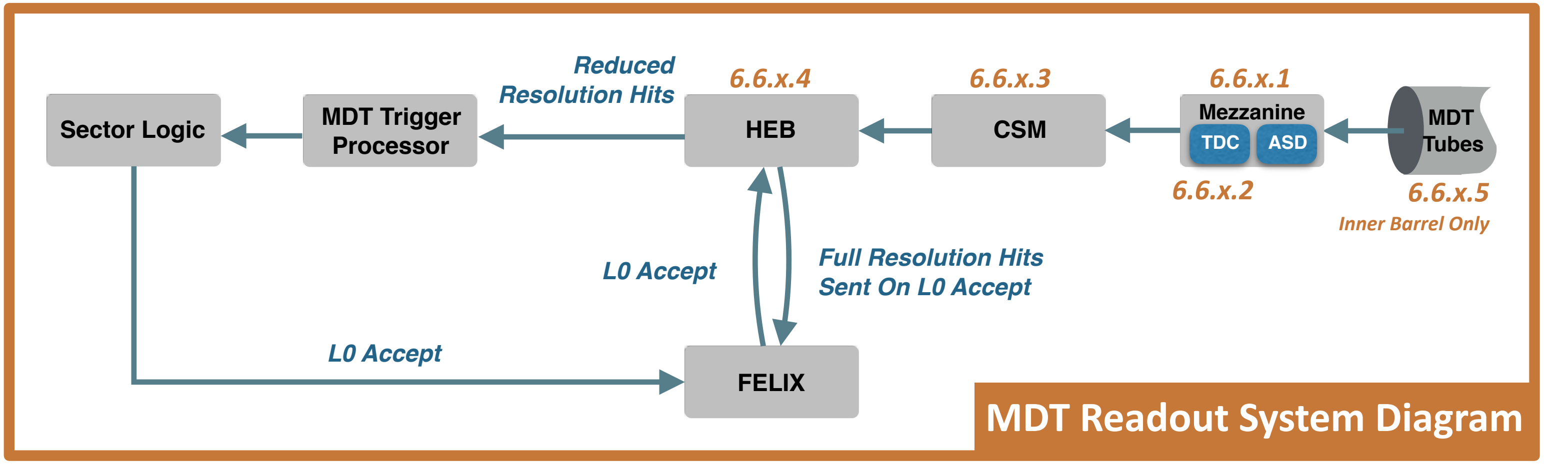
- Michigan developed the previous CSM currently used for MDT readout (see picture on right), and is currently developing a similar FPGA-based board for the Phase I ATLAS upgrade (New Small Wheel).



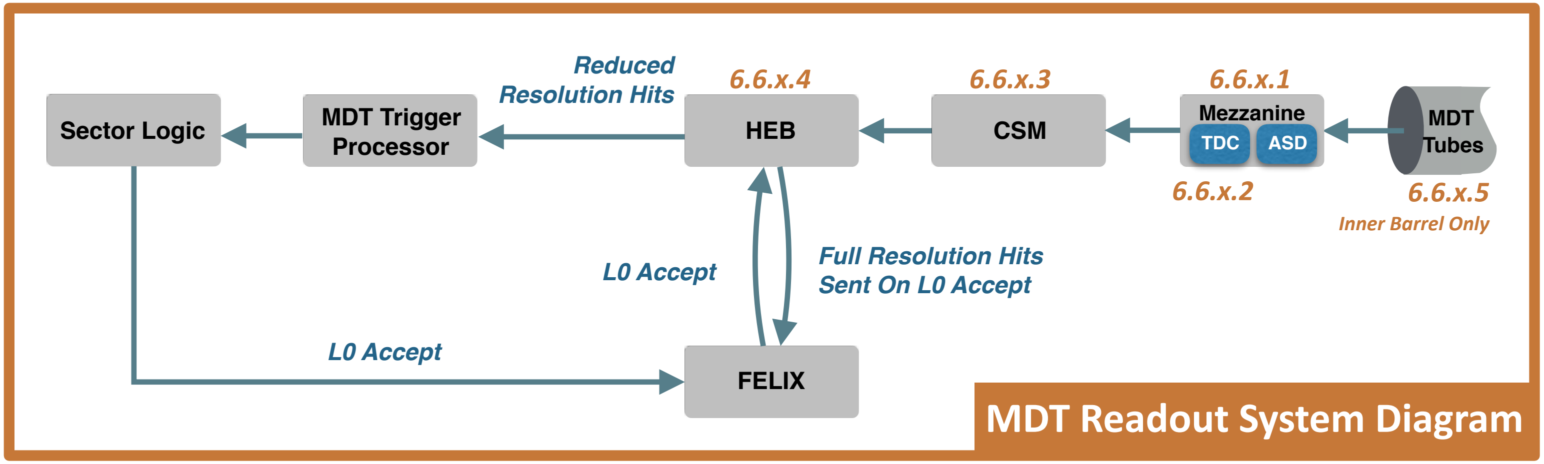


6.6.x.4 HEB

- The Hit Extraction Board (HEB) receives data from the CSM and buffers it. Lower resolution signals are extracted from data and sent to the hardware trigger. On a Level-0 trigger accept, the full resolution data is sent to data-acquisition (FELIX).
- 24 boards will be constructed by the University of Illinois (6.6.4.4). This represents 100% of the boards needed by ATLAS. There is no international competition.
- Illinois has a large electronics shop staffed with very experienced engineers in FPGA board design, who will be developing the HEB.



Summary of the NSF Scope



WBS	Deliverable	Functionality	# Produced by US	US Institutes	International Interests
6.6.x.1	**PCB for Mezzanine**	PCB board for the Mezzanine Card, which consists of three ASD and one TDC chips.	17,225 boards	University of Arizona ***6.6.1.1***	*none*
6.6.x.2	**Time-to-Digital Converter (TDC)**	Stores arrival times of the leading and trailing edges of the MDT signal (asic chip)	22,000 chips	University of Michigan ***6.6.3.2***	MPI (Collaborative), Japan
6.6.x.3	**Chamber Service Module (CSM)**	Data are formatted, stored, and sent via optical link to the Hit Extraction Board (HEB)	1300 boards	University of Michigan ***6.6.3.3***	*none*
6.6.x.4	**Hit Extraction Board (HEB)**	Sends reduced resolution hits to the trigger processor and on a Level 0 accept sends full resolution hits to FELIX for readout	24 boards	University of Illinois Urbana-Champaign ***6.6.4.4***	*none*
6.6.x.5	**sMDT**	Short monitored drift tubes to be paired with new RPC's on inner barrel for trigger	48 chambers	Michigan State University (tubes) ***6.6.5.5*** University of Michigan (chambers) ***6.6.3.5***	MPI and Protovino (Collaborative - 50%)

NSF Fraction of the Muon Upgrade

NSF FRACTIONS OF HL-LHC MUON SPECTROMETER UPGRADE

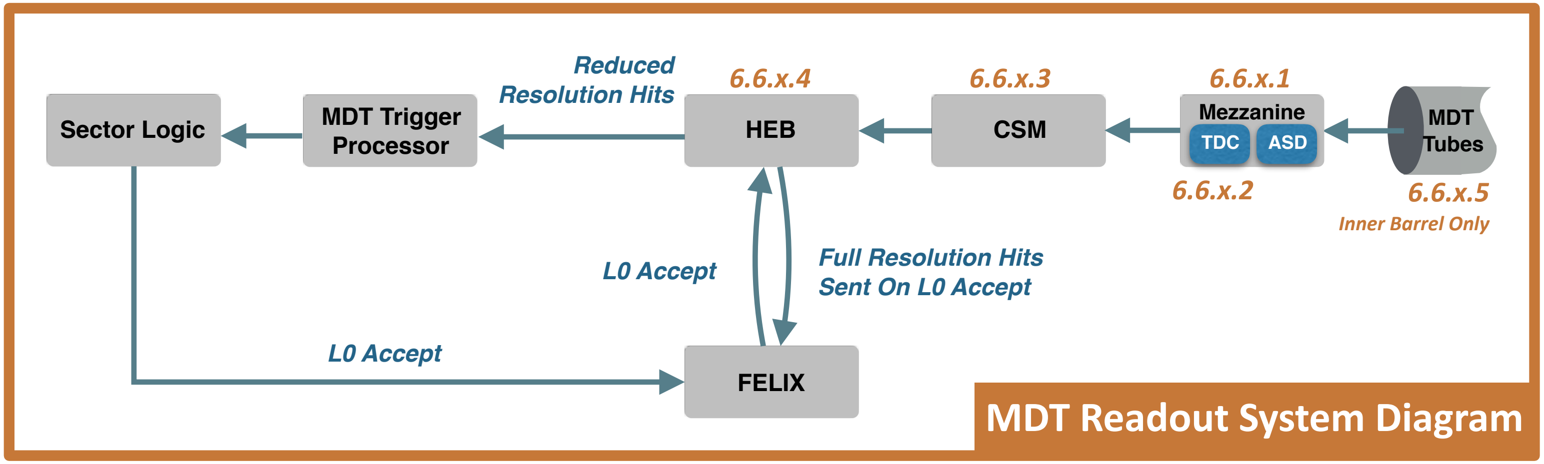
ATLAS WBS	ATLAS Item (Scoping Doc)	US WBS	Deliverable	NSF Fraction Design	NSF Fraction Production
5	**Muon Spectrometer**	**6.5**	**Muon Spectrometer**		**20%**
5.1	**MDT**				
5.1.1	sMDT detector				
			sMDT Tubes	50%	50%
			sMDT Chambers	50%	50%
5.1.2	sMDT installation basket				-
5.1.3	Mezzanine cards				
			PCB Board	100%	100%
			ASD		-
			TDC	100%	100%
5.1.4	CSM cards				
			CSM	100%	100%
			Hit Extraction Board	100%	100%
5.2	**RPC**				
5.2.1	Detectors				
5.2.2	Installation mock-up				
5.2.3	Installation tooling				
5.2.4	On-detector electronics (DCT)				
5.3	**TGC**				
5.3.1	On-detector electronics PS)				
5.3.2	sTGC on BW inner ring				
5.4	**High Eta-Tagger**				
5.4.1	Detector				
5.4.2	FE electronics				
5.4.3	Services and infrastructure				
5.5	**Power System**				
5.5.1	MDT				
5.5.2	RPC				
5.5.3	TGC				

Research & Development

- Each deliverable has developed an R&D plan to be prepared for construction
- sMDT's (UMich, MSU) tooling needs to be developed and tube construction begins before FY20 to allow for float in the existing ATLAS schedule
- PCB for Mezzanine (Arizona), TDC (UMich), and CSM (UMich) will be developing more advanced prototypes during R&D, as the construction timeline is slightly earlier due to the need to install electronics on-chamber for the sMDT's ➜ Front-End technology choices will happen at TDR (FY17)
- The HEB (Illinois) is off-detector electronics and therefore has a later timeline. Early R&D is more related to the design of trigger processing for the MDT's.

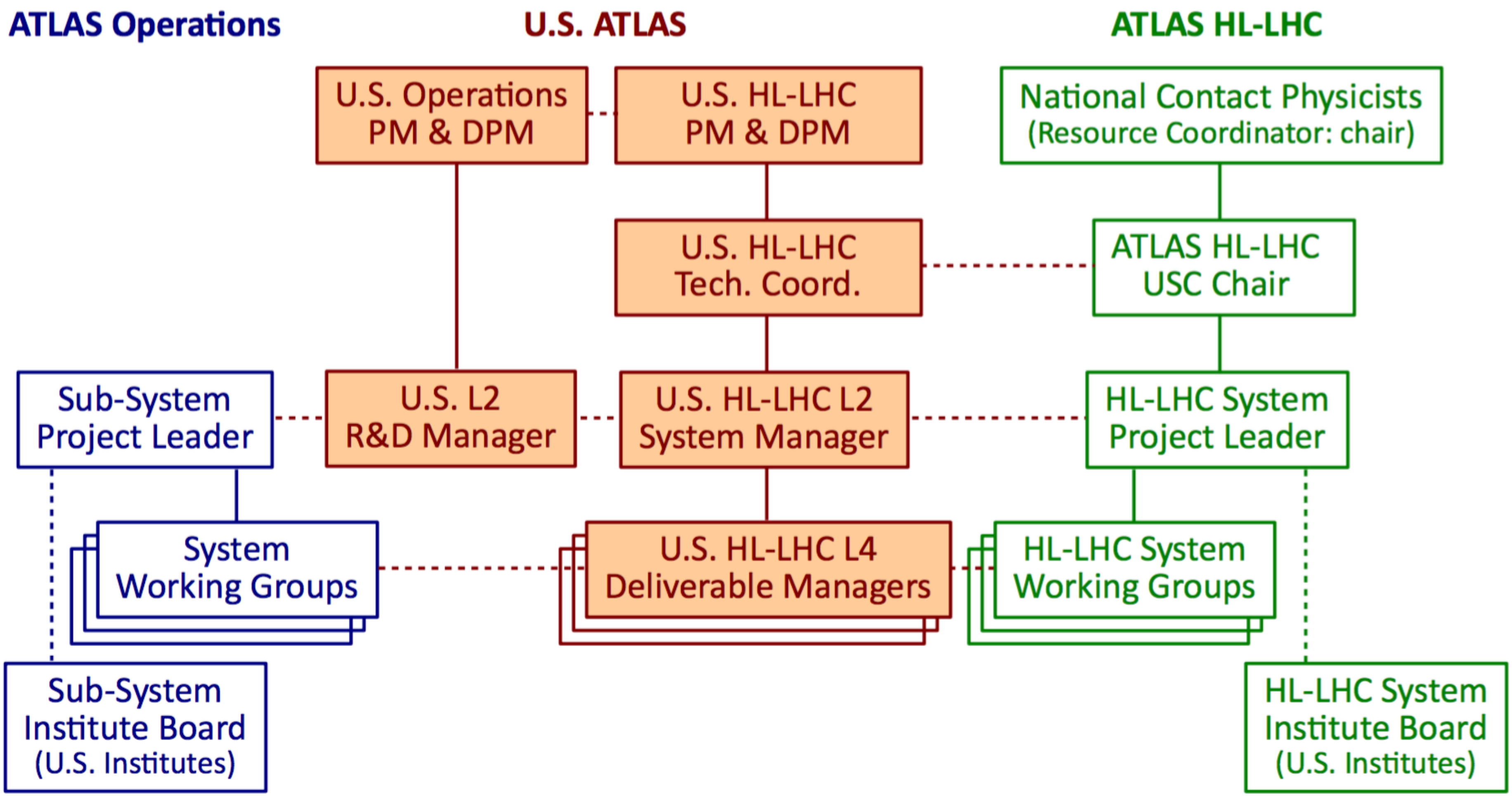
System Management & Integration

- Dan Levin (Senior Research Scientist at the University of Michigan) has agreed to act as Integration Engineer for the US HL-LHC upgrade of the Muon System.
- Primary Responsibilities
  - Organize “Expert Weeks” during R&D and pre-production
  - Organize reviews of designs and ensure CERN requirements have been met.
  - Monitor project schedules, identify and address any problems.
  - Liaison with the international ATLAS muon project leaders



MDT Readout System Diagram

ATLAS Organization

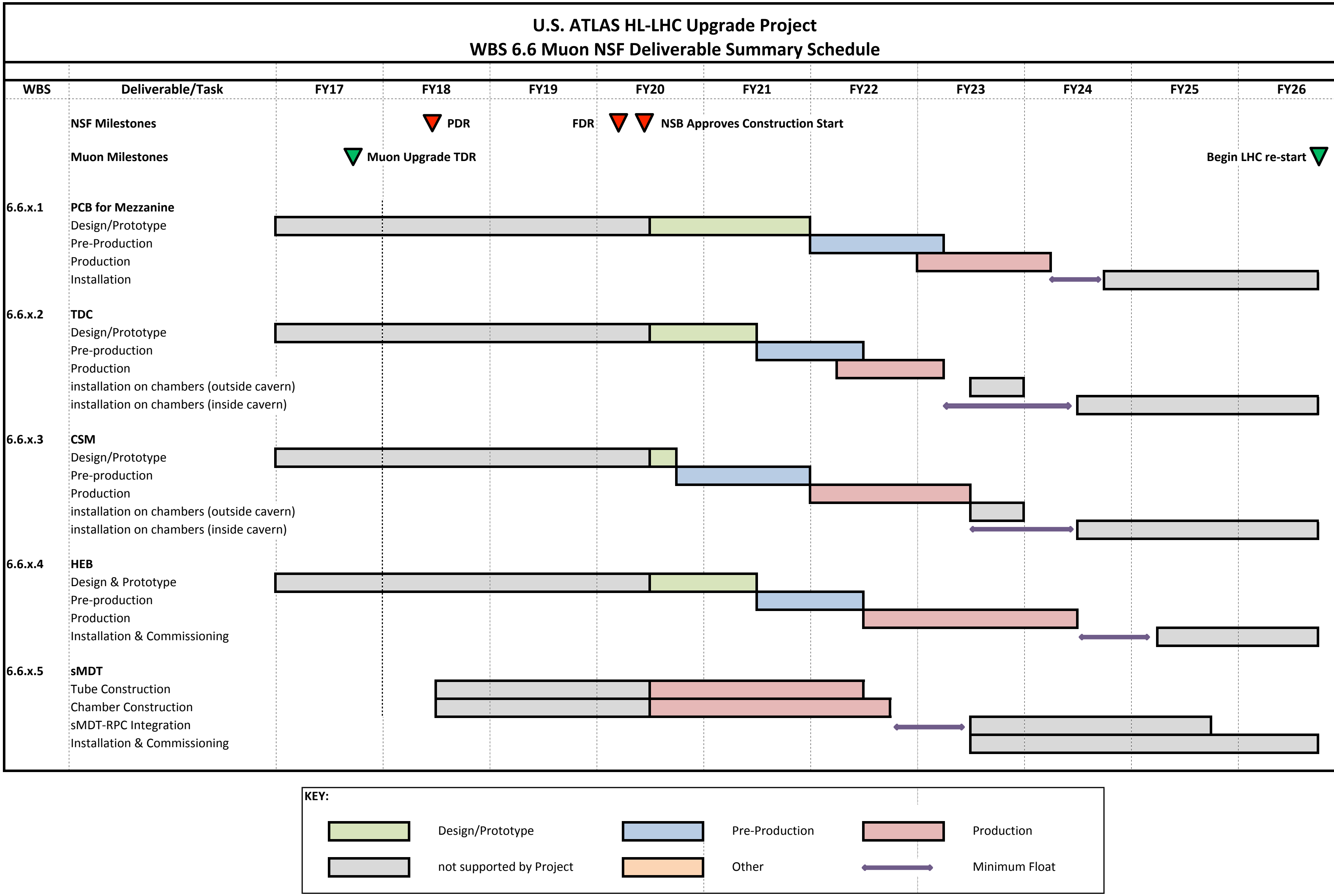


External Dependencies

HL-LHC EXTERNAL DEPENDENCIES FOR NSF DELIVERABLES

WBS	Title	Item	External Dependency	Mitigation Strategy
6.6	**Muon**			
6.6.x.1	Mezzanine Card		ASD (Germany)	Engineers at US institutes are closely collaborating with German institutues working on the ASD. Delays in the ASD will only affect pre-construction/construction. Based on the ASD timescale, several months of delay in final production of the ASD will not affect Mezzanine production. say 2 years of FLOAT
6.6.x.2	TDC		ASD (Germany)	Engineers at US institutes are closely collaborating with German institutues working on the ASD. Delays in the ASD will not affect the TDC development.
6.6.x.3	CSM		project is self-contained to NSF	
6.6.x.4	HEB		project is self-contained to NSF	
6.6.x.5	sMDT		project is self-contained to NSF	

Schedule built from scoping document and consultation with ATLAS management (particularly Muon Project Leader Christoph Amelung)



Risks

Low risk. More detail in the BoE's, which we can go through during breakout. Below represent the two largest risks for the project.

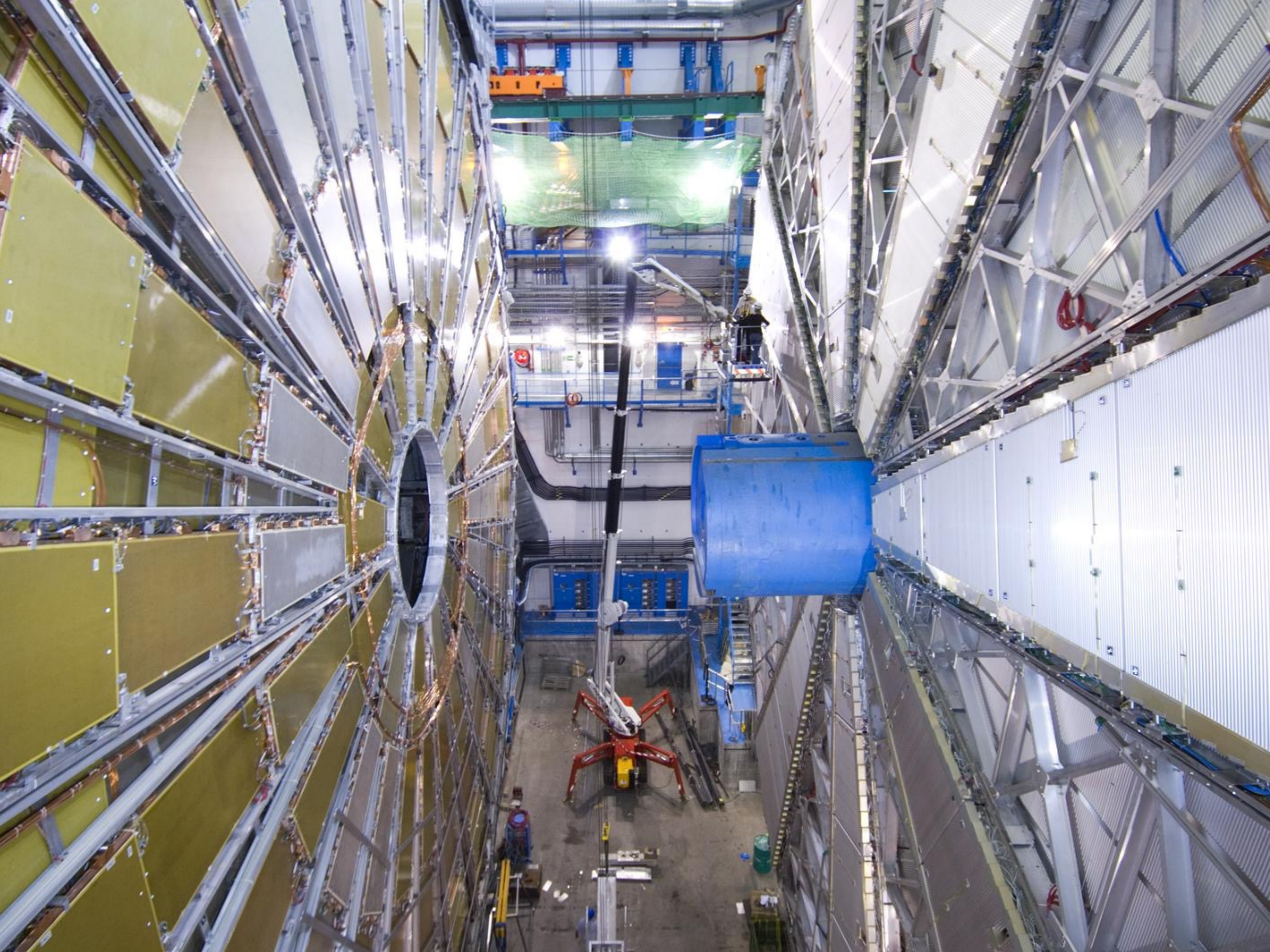
Schedule Risk:

- **Probability:** Low
- **Potential Problem:** Some mezzanine cards in the detector will be unreachable and therefore cannot be replaced.
- **Mitigation:** Jr EE hired to handle CSM firmware modifications such that these chambers can still be read out with the new front-end system.

Schedule Risk:

- **Probability:** Low
- **Potential Problem:** Current motherboard and cables that connect the mezzanine and the CSM cannot handle the data rates required for the new CSM and new Mezzanine. If the cables need to be replaced it will require more work on-detector.
- **Mitigation:** Tests have been performed on the current motherboard/cables to demonstrate they can handle required data rates for the maximum cable lengths needed for the new designs. We are only considering system designs that can utilize these cables.

Please see Risk Registry for more



Closing Remarks

- USATLAS taking on arguably the most impactful components of the HL-LHC upgrade for Muons.
- All deliverables led by institutes with previous experience and/or strong existing infrastructure.
- We are fairly invariant to ATLAS decisions. Projects are high priority and exist in all ATLAS scoping scenarios.
- The TDC and HEB face some international competition. Outcome for the HEB will be collaboration. The ASIC-based TDC could be an option not selected by ATLAS.
- The CSM and sMDT USATLAS projects are highest priority for ATLAS muon management.
- Institutes working on CSM, HEB, and TDC are already performing R&D towards developing a demonstrator system for the TDR (Due June 30th, 2017).

WBS	Deliverable	US Institutes
6.6.x.1	**PCB for Mezzanine**	University of Arizona ***6.6.1.1***
6.6.x.2	**Time-to-Digital Converter (TDC)**	University of Michigan ***6.6.3.2***
6.6.x.3	**Chamber Service Module (CSM)**	University of Michigan ***6.6.3.3***
6.6.x.4	**Hit Extraction Board (HEB)**	University of Illinois Urbana-Champaign ***6.6.4.4***
6.6.x.5	**sMDT**	Michigan State University (tubes) ***6.6.5.5*** University of Michigan (chambers) ***6.6.3.5***